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RESEARCH ARTICLE

Measuring the Creep Behaviour of Corrugated Board by Cascade and Individual Test Rig

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ABSTRACT

In this paper static and quasi-static test are conducted to determine the creep behaviour of corrugated board. This study shows a possible way to take the real loads occurring in container shipping into account. The aim of the measurements is to develop a new test option, which is in keeping with the loads occurring. Two test rigs have been developed and constructed for this purpose. These make it possible to measure the creep of corrugated board extremely precisely over a longer period in the aspect of climate chamber size and relative humidity (RH) distribution in the chamber. To increase the accuracy of measurement the analysis also covers those external and internal factors, which can influence the measurement of creep rates. The results show that these influences the accuracy of creep rate measurements to a significant extent, and considerable measuring errors can occur if these are disregarded. The final aim of this study in the future is to present a climate-dependent creep behaviour model for corrugated board using speed-dependent and relatively shorter tests by cascade and individual test rigs.

KEY WORDS

Corrugated board, creep behaviour, packaging, packaging material

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INTRODUCTION

Corrugated packaging and boxes are used as a well-known packaging to store, protect and transport goods such as raw materials, semi-finished products and finished products, respec-tively. According to a latest report on corrugated packaging by Smithers Pira the corrugated board consumption value will expand to 269 billion USD dollar in 2021 that means a consume of 160 million tonnes of board in that year [1]. Of course, the largest share of global packag-ing is accounted for paper and board packaging equating to about 40% of total market, grow-ing at an annual rate of around 4% [2].

Corrugated boxes made from board are usually placed in a stack during circumstances such as transport and storage, causing constant compressive loads for long time. These static compres-sive loads can cause significant and different type of deformation on boxes [3]. The reason of why this creep deformation is important is it can cause box failure at any applied load. This time can range from less than one hour to decades, with lower applied loads resulting in slow-er deformation and longer box lifetimes (time to failure from initial loading) [4]. Therefore, investigating and better understanding of corrugated board packaging performance for packaging engineers during real conditions such as long-term storage and transportation are necessary.

In the latest decades, dynamic tests (with standard atmospheric conditions) are usually used to determine the performance of corrugated boxes. Many packaging standard such as ASTM, ISTA and ISO uses these methods. In this case, the loads during shipping are compensated by using safety factors [5] and logically are not suitable to determine the creep behaviour The absence of international standards and guidelines is leading to an ever-increasing drive to in-vestigate the long-term behaviour of corrugated board that occurs in supply chain. The aim of this study is to present new test rigs and perform tests showing better accuracy as former re-searches showed. These two test rigs (one for ECT and one for BCT test) were developed and constructed for this purpose by BFSV (Beratung- Forschung- Systemplanung- Verpackung BFSV e.V.) (Fig. 1).

GENERAL INFORMATION

Corrugated board and humidity

As a result of its unusual structure, corrugated board possesses high strength at low weight [6]. Due to the hygroscopic behaviour of the fibres, humidity has a serious effect on these strength properties [7] [8] If the relative humidity (RH) increases from 50% to 90%, the BCT strength (BCT: box compression test) decreases by up to 60%. Other strengths, such as the ECT strength (ECT: edge crush test), also lose 55-60% of their strength [9] [10] [11] [12] [13]. Here has to be mentioned that probable BCT creep response for a series of samples can be inferred from ECT creep measurements [14]. In international shipping, there is also a further load on corrugated board due to stacking packaging boxes that are made from it. With high relative humidity and an additional load over a longer period of exposure, the corrugated board starts to creep [15] [16]. Due to the relatively few research project in the topic of creep behaviour of corrugated board

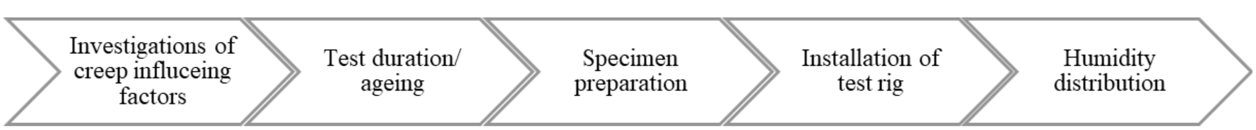

Fig. 1: Overview of the conducted investigations.

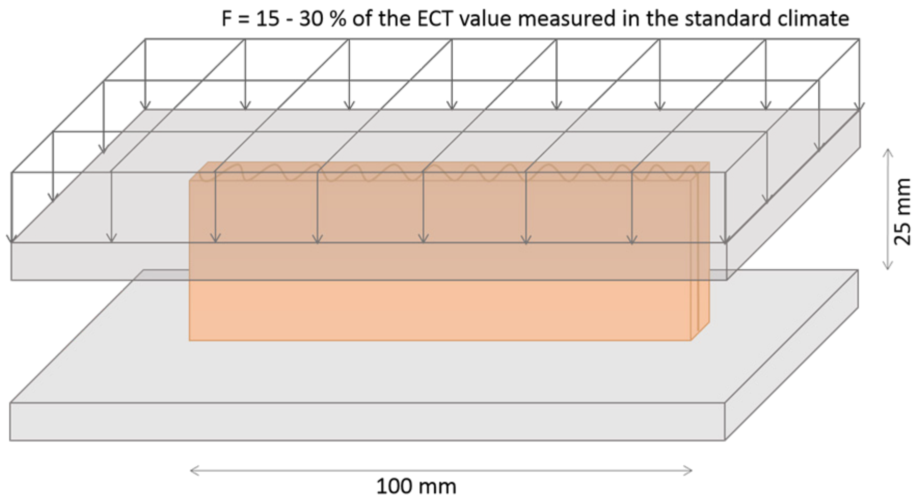

Fig. 2: ECT creep rupture test (with 30% of ECT value measured in standard climate).

[17] that is why BFSV has developed and commissioned two new test rigs that can be used to investigate the creep behaviour of corrugated board.

ECT test rigs

Both new test rigs were modelled on test facilities designed for creep rupture tests on the creep behaviour of metallic materials and the test rig for measuring the ECT strength of corrugated board specimens [18]. When testing the ECT strength, a standard 25x100 mm specimen was loaded perpendicular to the corrugations of the corrugated board (Fig. 2).

Both test rigs, the cascade test rig (Fig. 3,4 left, descBoth test rigs, the cascade test rig (Fig. 3,4 left, described by Sadlowsky et al. [19]) and also the individual test rig (Fig. 3,4 right, described by Köstner et al. [20]), test according to the same principle. In this case, the specimen is loaded perpendicular to the corrugations with a constant load of 25% of the maximum ECT value, as this corresponds to the safety factor most commonly used in practice. During the test, the test apparatus is located in a climate chamber with a defined eight-hour climate cycle (test starts at 50% RH for approx. 1.5 hours until the change to 90% RH, temperature constant at 23 °C). The only difference between the two test rigs is that four specimens can be tested simultaneously with the cascade test rig whereas the individual test rig was developed for examining one specimen in the laboratory environment [19] [20].

Long-term measurement

Fig. 5 below shows the course of a long-term measurement by ECT specimens where the blue line represents the climate prevailing in the climate chamber. The climate alternates between a relative humidity of 50% and 88% at a constant temperature of 23 °C. The red line reflects the deformation behaviour of the ECT specimen over the test period. Superposition of the swelling behaviour and the creep caused by the compressive load leads to the creep deformation increasing in the drying phase and decreasing in the moisture penetration phase. At the end of a test, the lifetime [h] or the time to failure of the specimen and the mean creep rate [mm/h] are noted. The mean creep rate represents the increase in creep deformation per unit of time

Fig. 3: Test rigs for measuring the creep behaviour of corrugated board specimens (left: cascade test rig; right: individual test rig).

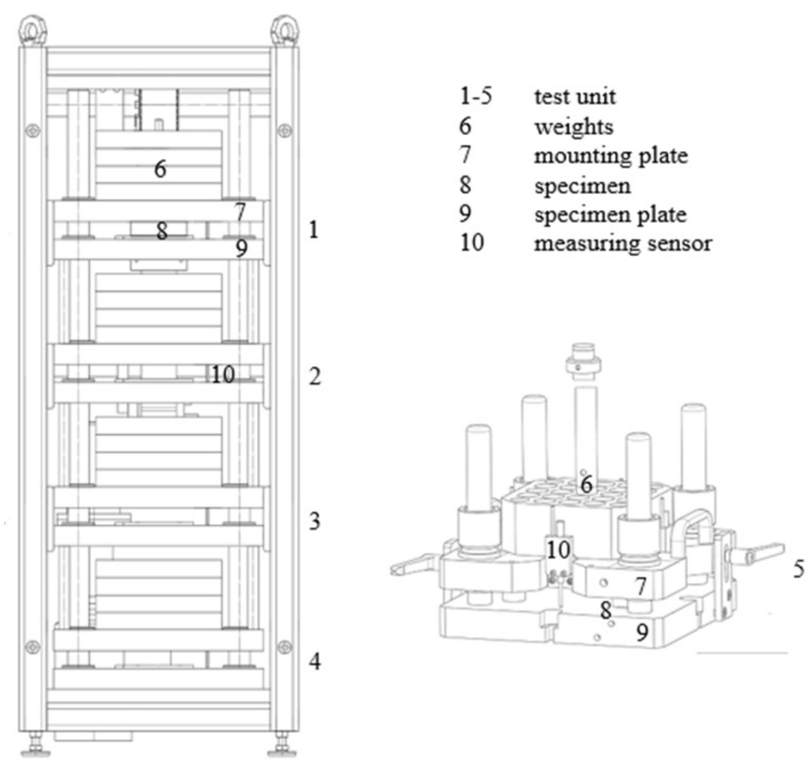

Fig. 4: Schematic representation of both test rigs (left: cascade test rig; right: individual test rig).

in the secondary phase of the creep process. The lifetime indicates the time from the start of the test to failure of the specimen. The specimen loses strength significantly at the time of failure (Fig. 6). The mean creep rate and the lifetime serve as comparative values for assessment of the specimen.

FACTORS ON CREEP

Examining a possible influence that disruptive factors can have on the investigation results of measuring the ECT strength in the long-term test (ECT long-term measurement) plays a decisive role in the development of the new test methods. It is necessary in this case to differentiate between factors that can and cannot be influenced.

Cannot be influenced factors

Factors that cannot be influenced, such as production parameters, environmental conditions and material parameters, cannot be identified by an in-depth visual inspection of the specimens before the test begins. They are unavoidable but have a strong influence on the test results [21].

Production parameters, which vary from one corrugated board machine to the next, have a serious influence on the strength properties of the corrugated board [8] [14]. The ECT and BCT in particular are affected. Production influences, for example, are fishtailing (crooked edge gluing), gaps (areas without glue) and localised crushing [22] [23].

The climate, particularly the relative humidity in this case, is one of the main environmental conditions. The fibres in the corrugated board papers are hydrophilic and adapt to the particular environmental humidity with the mechanical strengths decreasing at high humidity [24] [25]. In humidifying and dehumidifying phases, the superposition of irreversible swelling and shrinkage effects leads to structural transformations in the fibre network which strongly influence the strength properties of corrugated board [26] [27].

Material parameters, for example, are ageing of the material, local differences in fibre density and fibre strengths. Above all, fluctuations in the fibre strengths and the strength of the fibre-fibre bonds have a serious influence on the creep behaviour of the corrugated board and the behaviour of the material in the alternating climate. The behaviour of the material is also highly dependent on the proportion of recycled fibres. If the proportion of recycled fibres increases, then the fatigue strength of packages made of corrugated board decreases.

Can be influenced factors

Detailed investigations of the test sequence and test setup can determine and thus prevent factors that can be influenced. Factors that can be influenced include the following points: specimen preparation, the test setup or test rig, humidity distribution, and the effect of external mechanical loads.

Specimen preparation has a serious effect on the creep behaviour. First of all, cutting of the loaded edges of ECT specimens must be exactly parallel so as not to adversely affect the results. In this case, the condition of the saw blade and the number of specimens already sawn with the saw blade play a significant role. A further important point is conditioning of the specimen material in standard climate conditions (23°C/50% RH) before starting the test [28].

Both test rigs for observing the ECT long-term value are developments by the BFSV. It is imperative to examine the test rigs in detail when commissioning in order to generate reproducible and comparable results. When the test rigs were started up, it was found that reproducible results could only be achieved after several series of tests and conversion measures [19] [20]. The plane parallelism of the test plates, for example, was measured precisely since this has a significant influence on the measurement results.

Creep tests are carried out in climate chambers in which a standard, humid or alternating climate can be adjusted. There may be variations in the distribution of

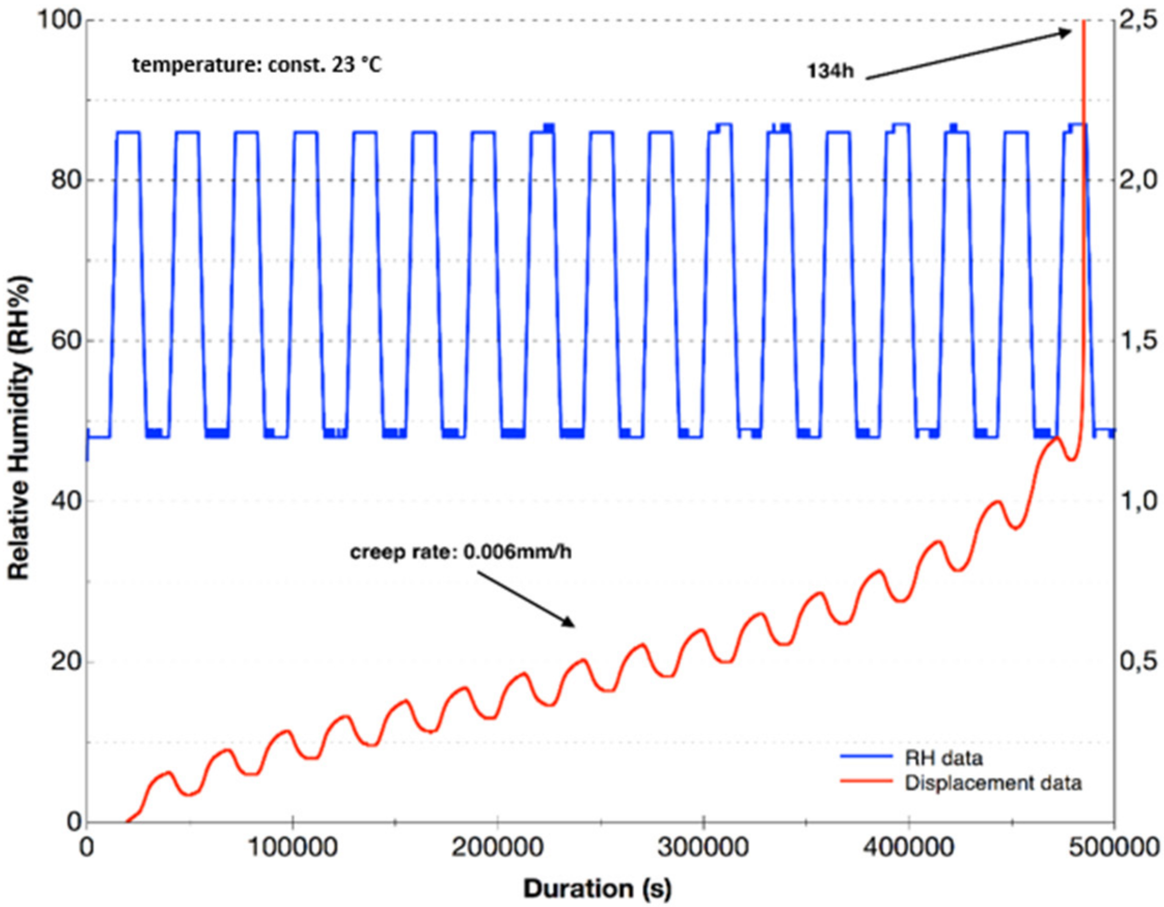

Fig. 5: Creep behaviour of a corrugated board specimen in alternating climate at constant temperature 23 °C.

humidity and temperature due to using different types of climate chambers and chamber sizes. In addition, the geometry of the test rigs and their arrangement inside the climate chambers can also exert an influence of the measurement of creep rates.

External mechanical impacts are another factor that can be influenced. Vibrations and oscillations due to other power units running in the vicinity can act on the chamber and thus on the test rigs via the floor and have an adverse effect on the test.

RESULTS

After a detailed investigation of possible influencing factors on the measurement of creep processes in ECT specimens, four factors have proved to be particularly important: the test duration and thus ageing, sample preparation, installation of the two test rigs and investigation of the humidity distribution in the climate chamber.

Test duration and ageing

Specimens of two different wet-strength corrugated boards are examined at intervals of nine

Fig. 6: Corrugated board specimen after creep test in altering climate at constant temperature 23 °C.

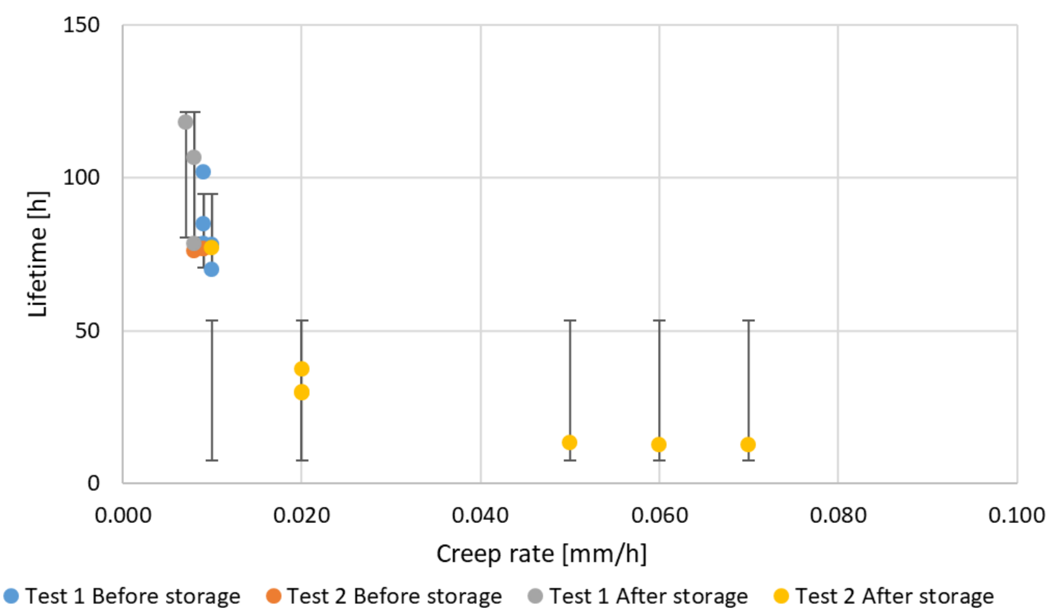

Fig. 7: Ageing influences on the long-term behaviour of ECT specimens (cascade test rig).

months (Fig. 7 - Test 1) and 24 months (Fig. 7 - Test 2), the specimens being stored in normal climate conditions for corrugated board 23 °C/50% RH for the entire storage period. The storage period and storage conditions of the corrugated board at the manufacturer's premises before delivery to the BFSV laboratory are not known. All other test conditions are kept constant. The results of the tests are illustrated in Fig. 7.

Fig. 8 shows that the storage period and the unknown climatic conditions during this period between manufacture of the corrugated board and testing have an effect on the creep behaviour of ECT specimens. At the beginning of both tests, the corrugated boards have similar creep rates but after 24 months' storage the creep rate is four times as high as before storage, while the lifetime has more than halved (Fig. 8).

When looking at the standard deviations in Fig. 7, it becomes clear that the values spread widely above all after 24 months of storage. The standard deviation of the lifetime in Test 2 is 0.4 hours before the storage period and 22.9 hours after the storage period. If the standard deviation of the nine-month test is considered, it becomes clear that the measured value can also be due to the natural variability of the corrugated board. Thus, storage of up to nine months could take place without exerting any adverse effects on the creep behaviour. Storage beyond this time would need to be investigated further but it is clear that storage of two years has an adverse effect on the creep behaviour. The extent of this adverse effect would have to be substantiated by investigating further corrugated boards. All in all, it is important when determining creep rates to avoid preceding long storage times of the material to be investigated.

Specimen preparation

Consistent specimen preparation is very important to ensure virtually constant quality of the specimens. All specimens are conditioned at 23 °C/50% RH before starting the test. Cutting of the specimens is carried out by only one person on the same circular saw with the same saw blade. In addition, all specimens are accurately measured before the

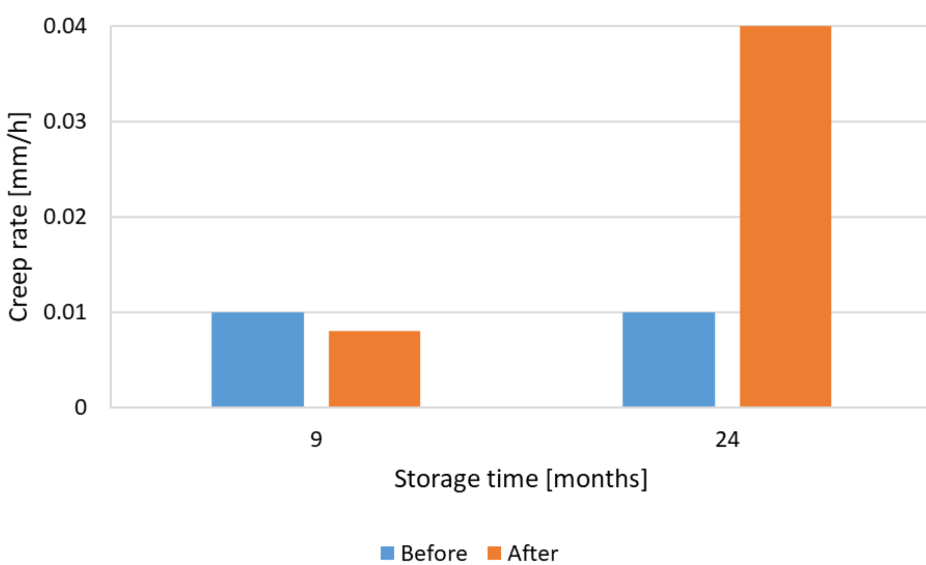

Fig. 8: Ageing influence on the creep rate of ECT specimens (cascade test rig) (n = 10).

test and the corrugations are examined for integrity. Thus, any influence exerted by specimen preparation on the result of the investigation is marginal. The specifications of corrugated board specimens to the tests are the follows:

- Flute combination A-B-C
- Thickness 13.1 mm
- Basis weight 1789 g/m²
- Edge-Crush-Test 24.52 kN/m
- Puncture resistance 30.6 J
- Bursting strength 4704 kPa
- Wet bursting strength 1415 kPa
- Water resistance: no separation of layers after 24 h in water

Installation of the test rig

Before starting the test, a spirit level is used to align the test rigs horizontally and vertically. The plane parallelism of the test plates in particular has a serious effect on the ECT value. For this reason, the plane parallelism of both test rigs has been investigated in several studies that have already been published. Any adverse effect due to the plane parallelism of the test plates of both test facilities on the investigation results was classified as low.

Thus, in theory the influence of the test setup and the test rig (cascade or individual test rig) can be regarded as low. Several test series will be carried out to support this statement. In this case, both test fixtures will be arranged next to each other in the 1 m³ chamber of the BFSV in such a way that the test level of the individual test rig is located at almost the same height as the specimen to be tested in the cascade test rig. A wet-strength, triple wall corrugated board will be tested in an eight-hour alternating climate. Fig. 9 shows the results of one test series.

Fig. 9 shows that in some cases measured values of the individual test rig are higher than those of the cascade test rig. The mean creep rate in the individual test rig's results is 0.008 mm/h while that in the cascade test rig is 0.010 mm/h. The standard deviations of the measured values are similar for

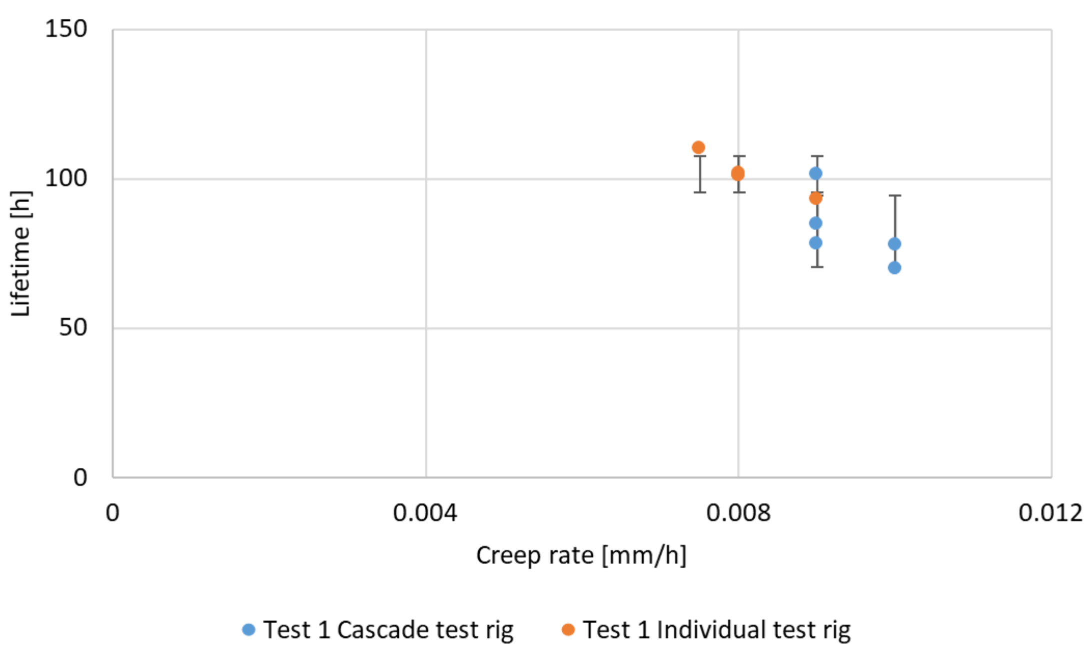

Fig. 9: Comparison of the ECT long-term test rigs.

all results and are therefore considered to be fluctuations due to the raw material. Better mounting of the test plates may be one reason for the higher lifetimes in the individual test rig. The four-column setup enables precise guidance of the test plate, allowing it to be set down evenly on the specimen. The test plates of the cascade test fixture are guided via two columns, which may result in the plate being set down on the specimen slightly crookedly, which is not visible to the naked eye. As a result the weight is set down on the specimen unevenly. This can lead to the specimen being damaged and consequently have an effect on the measured values. The difference between the measurements of both test rigs will be investigated in further test series to rule out the corrugated board's natural variability as the reason for this difference.

Humidity distribution

The ECT long-term measurement is carried out in a 1 m³ climate chamber of the BFSV (manufactured by Noske-Kaeser, Germany). The chamber is maintained at regular intervals, and temperature and humidity monitoring is carried out using an aspiration psychrometer according to Assmann. Various tests are performed using climate sensors in order to exclude the influence of the test apparatus' geometry and positioning of the measuring instruments on the distribution of humidity in the chamber. The aim of these tests is to make it possible to check the humidity distribution in the climate chamber. In six tests, four humidity sensors (F1 - F4) are placed in different locations on the two test rigs in the climate chamber. Positioning on the individual test rig also varies in height. Table 1

Table 1: Test setup for humidity monitoring (F1 - F4 = humidity sensor position, xxxx = position of individual test rig).

Location							
		1st	2nd	3rd	Table	4th	Base
Test 1	Height (HI) Cascade (C) Individual (I)	F2		F3	xxxx F1/F4		
Test 2	HI C I	F2		F3	xxxx F1/F4		
Test 3	HI C I	F2		F3		xxxx F1/F4	
Test 4	HI C I	F2		F3		F4	xxxx F1
Test 5	HI C I	F2		xxxx F3 F1		F4	
Test 6	HI C I	F2	xxxx F3 F1				

shows the arrangement of the test setups. To illustrate the test setup, the first test is described below by way of example. (Table 1 - Test 1). If the climate chamber is viewed from the front, the cascade test rig (C) is on the left and the individual test rig (I) is on the right. A laboratory table is used to bring the individual test rig to a height (HI) between the third and fourth level of the cascade test fixture. The humidity sensors are located at the height of the first and third test levels of the cascade test fixture and on the front and rear of the individual test rig.

Before the measurement begins, all humidity sensors are calibrated to ensure the accuracy of the results. Fig. 10 shows the recording of a climate investigation by way of example. Here the abbreviation "F" stands for humidity sensor and "T" for temperature sensor. The eight-hour alternating climate is mapped by the humidity sensors F1 - F4. The relative humidity is kept constant at 50% RH until it increases to 90% RH in a one-hour transition phase. This is followed by a three-hour phase at 90% RH. The next step is a one-hour transition phase to 50% RH and the cycle begins again. The temperature sensors T1 - T4 show the temperature held constant at 23 °C.

Fig. 11 shows a detailed view for better illustration of the humidity sensor recordings. It is clear from this that the sensor recordings differ by no more than 1% RH (Fig. 11 gap between relative humidity % F1 to F4).

The results of all the tests can be taken from Table 2. The mean deviation represents the standard deviation of the calculated mean value for the measured values of the four sensors. Consequently, the maximum deviation indicates the largest measured difference between the recordings of the four sensors. When looking at the results, it becomes clear that the maximum deviation of the measured values is 1.1% RH in Test 4.

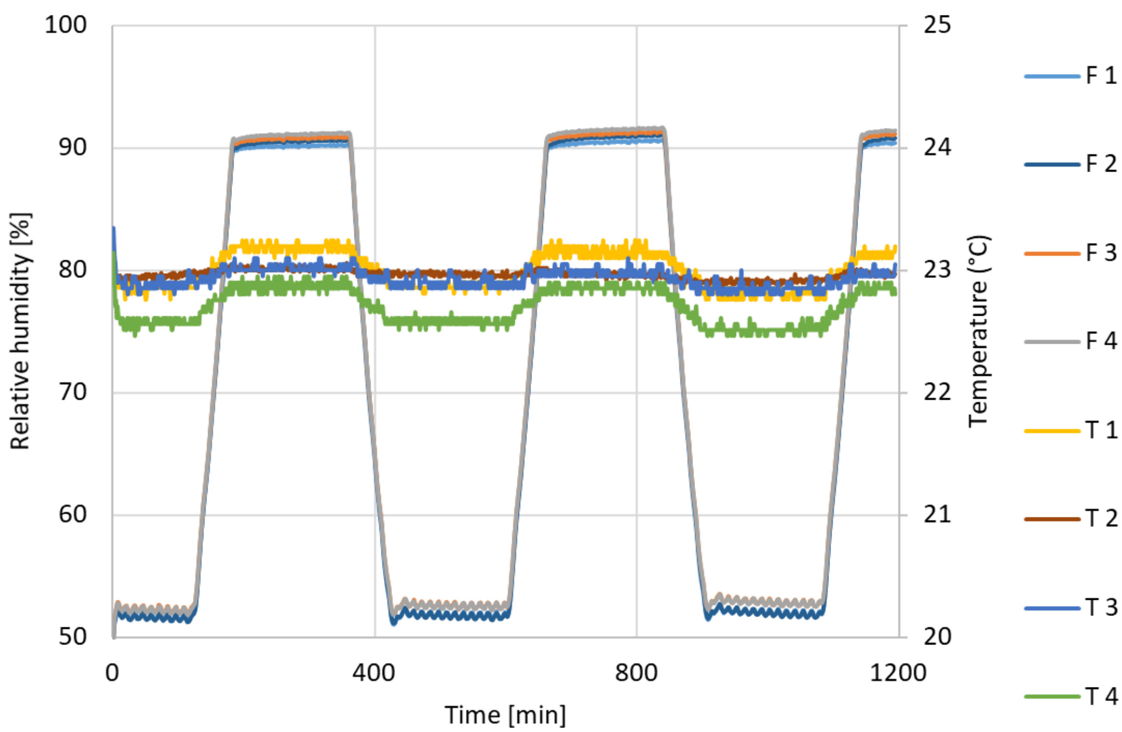

Fig. 10: Recording the humidity distribution in the 1 m ³ climate chamber (F1 – F4).

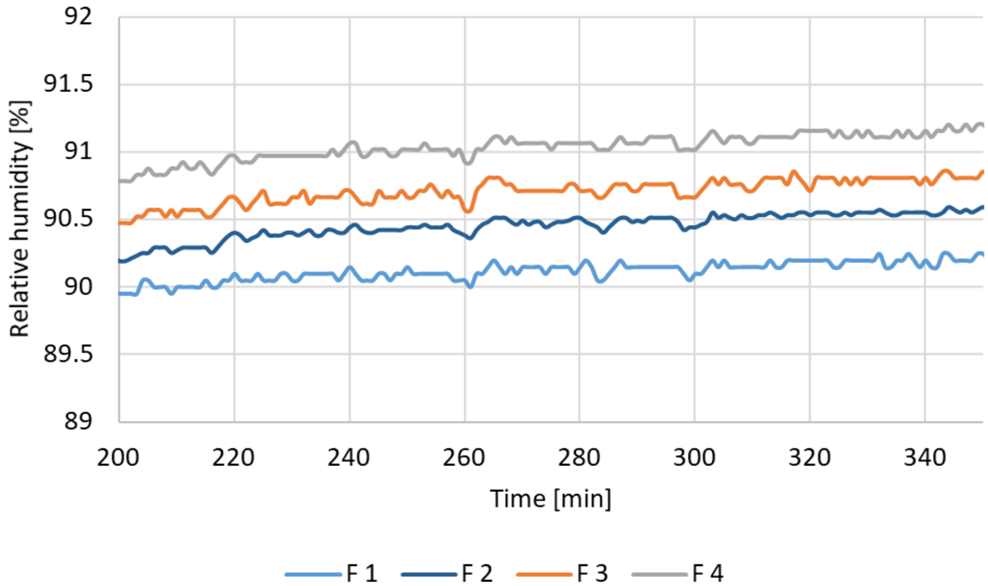

Fig. 11: Detailed view of the humidity sensor recordings.

To evaluate the results shown in Table 2, it is necessary to include the deviations in relative humidity permissible according to the current standards such as ISO 2233:2001-11, ISTA Series (e.g. ISTA 2A) and ASTM D4332-01:2006-11 [29] [30] [31]. All these standards specify the permissible deviation in relative humidity as ± 5%. Thus, the maximum deviation of 1.1% is within the scope of the limit value required by the standard. As the deviation is so small, further investigations into the humidity distribution in the 1 m³ climate chamber will be abandoned.

In summary, the influence of the humidity distribution in the 1 m³ climate chamber on the test results is considered to be low. The dehumidifying condenser has to work hard due to the alternating humid and dry phases in the eight-hour alternating climate. The process of switching the compressor on and off can cause vibrations inside the chamber. Comparative tests were carried out in a further chamber to examine this external mechanical influence on the measurement results. The chamber has a volume of 8 m³. External vibrations can only reach the interior of the chamber to a small extent owing to the chamber's construction. However, difficulties may arise during execution of the eight-hour alternating climate due to the size and mode of operation. The setup and arrangement of the two test rigs and the material of the specimens remain unchanged. The results are presented in Fig. 12 below.

Table 2: Results of measuring the relative humidity in the 1 m ³ climate chamber.

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Mean deviation [% RH]	± 0.41	± 0.50	± 0.69	± 0.65	± 0.57	± 0.56
Maximum deviation [% RH]	0.52	0.79	0.95	1.1	0.75	0.79

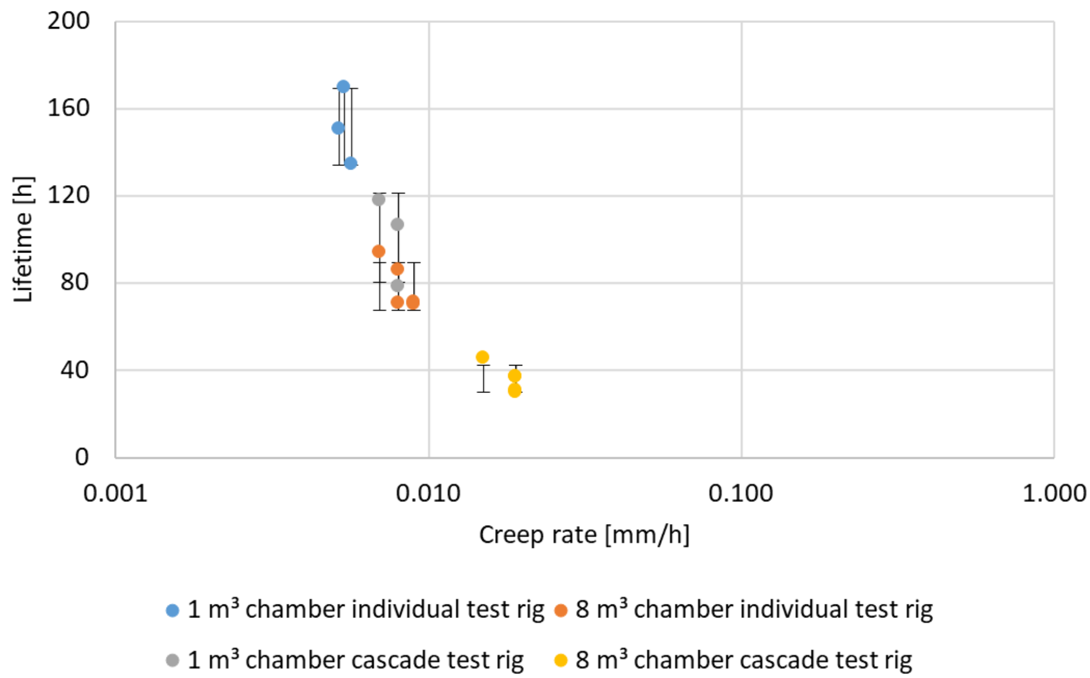

Fig. 12: Comparative tests in different climate chambers.

It becomes clear from Fig. 12 that the measurement results of the 1 m³ chamber are almost twice as high as those of the 8 m³ chamber. Based on the example of the creep rates from the individual test rig, this means that a creep rate of 0.005 mm/h was measured in the 1 m³ chamber and a creep rate of 0.008 mm/h in the 8 m³ chamber. The difference becomes even more obvious when looking at the lifetimes. A lifetime of 151 hours was achieved in the 1 m³ chamber, whereas the lifetime in the 8 m³ chamber was 78 hours. The reason for the deviations might be due to how the 8 m³ chamber implements the alternating climate. Maintaining the humid phase for longer results in a shorter lifetime and thus in an increased creep rate.

SUMMARY REMARKS

The test rigs developed by the BFSV show reproducible creep rates of corrugated board specimens. Due to the sensitivity of the measurement, it is imperative to examine all the factors influencing the measurements in detail before starting the test because external factors can have a major effect on measurement of the creep rates. Owing to the inhomogeneity of the corrugated board packaging material, care must be taken when carrying out the test to introduce as many constant factors as possible. The first step should be to ensure that the storage times of the corrugated board samples from production up to testing are kept relatively short. Preparation of the specimens should take place according to a defined plan and should be carried out and supervised by a trained tester. The quality of specimen preparation can additionally be verified by means of round robin tests. It is also indispensable to keep the test setup constant, for example the arrangement of the test rigs in the climate chamber or the type of climate chamber, to maintain the chambers regularly and to calibrate the climate measuring equipment carefully.

CONCLUSION

In this research project, launched in October 2015, attempts are being made to calculate the climate-dependent creep behaviour of corrugated board using speed-dependent and relatively shorter tests by cascade and individual test rigs. As a result, it should become possible to use time- and money-saving short-term tests to estimate the long-term behaviour of corrugated board. Thus, in future, it may be possible to better utilise the potential of the packaging material, prevent transport damage and protect the environment.

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